Resources Allocation in Disaster Response using Ordinal Optimization Based Approach

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***Abstract*—Recent events, such as Hurricane Katrina, have revealed the need for coordinated and effective disaster responses. An optimal distribution of available resources is essential for disaster response effectiveness. Emergency responders are faced with the challenges of increased size and complexity of critical infrastructures that provide vital resources for disaster response operations. In this paper, we propose a simulation-based tool to assist emergency responders in finding the optimal distribution of available resources during a disaster event. The proposed tool utilizes the Disaster Response Network Enabled Platform (DR-NEP) which is an infrastructure interdependencies simulation platform for disaster response support. DR-NEP is a simulation network platform that integrates different simulators for different infrastructures to form a universal simulation platform. We employ a new concept in Discrete Event Systems optimization called Ordinal Optimization to address the problem of resources allocation during a disaster event. The objective of the optimization problem is maximizing the operational capacity of a critical infrastructure, a hospital in this case. Due to the huge combinatorial feasible search space, an Ordinal Optimization based approach is used to solve the problem using two main concepts: goal softening and order comparison. This approach aims at finding a Good Enough solution set (G) with an acceptable probability and efficient computational effort. This paper describes early results of our work that shows the use of our approach in optimizing resources allocation in a simulated disaster event.**

I. Introduction

Disaster responders are faced with increasingly challenging decisions as the size and complexity of cities and districts grow. During large disasters, different infrastructures (power networks, water networks, health system, and communication networks, etc.) are affected simultaneously. Successful response to such disaster requires efficient allocations of available resources. This, in turn, requires effective coordination across these infrastructures. To analyze such scenarios, an interdependencies simulator can be used to assess the impact of operator decisions on the infrastructures behavior [1]. Introducing interdependencies simulator can be very effective to support emergency decision making due to the capability of modeling, sometimes hidden interdependencies that determine resources requirements and distribution. The adopted strategy for resources allocation should lead infrastructures to feasible operating states optimized for global objectives (e.g. maximizing human well-being and minimizing economic losses). As an example of feasible physical state, the energy level supplied to an electrical load is limited by the maximum current level of the corresponding electrical feeder and cannot exceed a certain threshold. This requires the interdependencies simulator to employ a physical infrastructure model which enables at the same time the simulation of the infrastructure at the funtional level. A Technological Infrastructure Simulator (Domain simulator) can simulate each physical system independently (e.g. Power grids, Telco networks, water distribution and transportation systems) and validate the feasibility of the physical state reached by each system. A unifying framework that provides decision assistance during real-time resources allocation during disasters by eliminating non-feasible options from consideration is needed to evaluate quantitatively the impact of interdependencies on the simulated decision outcome.

There are many research efforts that focused on optimizing allocation of available resources during disasters. Most of these efforts exist within operations research literature [2]. They address different disaster types such as wildfires [3], earthquake [4], and public health emergencies [5]. Different approaches have been developed to model the disaster scenarios including: mathematical formulation [6], and stochastic simulation model [3]. In this work, we employ existing physical domain simulators to form a simulation-based environment for modeling disaster events. Then, we developed an Ordinal Optimization based approach to find the optimum allocation of available resources. A simple disaster scenario is modeled and presented to show the validity of the approach.

II. Disaster Response-Network Enabled Platform

The Disaster Response Network Enabled Platform (DR-NEP) is a web services based software platform that integrates different simulators by communicating their results to each other. It uses a common enterprise service bus (ESB) and a database for establishing this communication. This architecture creates a distributed computing architecture for the purpose of assisting decision making. Every simulator is connected to DR-NEP using a software adapter that listens to the ESB for instructions to run simulations, gather inputs from simulators and the database, and push results from the simulators back into the database. Once the simulators and the adapters are configured, a controller in the ESB pushes input into the simulators at regular intervals, which can be predetermined before the simulation. In addition, DR-NEP offers web pages

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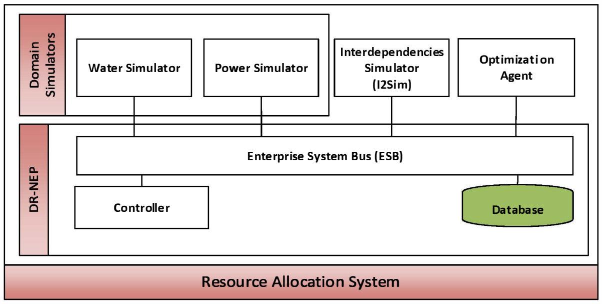

Fig. 1. DR-NEP Architecture.

and mapping services for researchers and disaster responders to coordinate with each other and visualize resources flow and infrastructures operability. The interactions between DR-NEP components are shown in Fig. 1.

A. Infrastructure Interdependencies Simulator (i2Sim)

i2Sim Simulator [7] is an event driven time-domain simulator for modeling infrastructure interdependencies. i2Sim uses a cell-channel approach to build a simulation environment that provides a multi-system representation of multiple Critical Infrastructures (CI) at multiple hierarchical levels (local, municipal, provincial, etc.). The simulator assesses in real time the effects of resources allocation decisions during disasters. i2Sim can be integrated with other simulators to study the impact of one infrastructure on other interdependent infrastructures. The DR-NEP architecture enables i2Sim to exchange simulation results with other simulators via software adapters [8].

B. Domain Specific Simulators

Domain simulators are used in DR-NEP architecture to simulate the detailed topological configuration of the infrastructure. Specific calculations such as Load Flow analysis for power system and steady state water flow for water system are performed using the domain simulators. Disaster events are modeled in the simulators to find the available resources under these conditions. The results of these calculations are then pushed into DR-NEP database using software adapters [9]. During disaster simulation, i2Sim simulator uses these results to find the optimum allocation for the available resources. In this paper, MATPOWER [10] and EPANET [11] are used as domain simulators for power and water systems, respectively.

III. Problem Formulation

The resource allocation problem considered in this paper includes several subsystems. Details and modeling assumptions for each subsystem are given below.

A. i2Sim Model

The i2Sim model used in this paper shows a high level abstraction of the disaster site. In i2Sim ontology, physical entities such as hospitals and power stations are modeled as cells connected by channels. Each cell models its infrastructure using a non-linear input-output function described by i2Sim Human Readable Tables (HRT). The HRT determines the output of the cell, e.g. treated patients in a hospital, based on its physical damage and available input resources. The physical damage of the infrastructure caused by a disaster is modeled using i2Sim Physical Mode (PM) rating. Resources such as electricity and water are produced and consumed by the cells and transported by the channels. Flow of these resources can be controlled using i2Sim distributors outputs. The distribution ratios for the resources are determined by the optimization agent to represent the optimal allocation.

B. Power System Model

The power system model shows the details modeling parameters of a power distribution network for the disaster site. The model includes substations transformers, sectionalizing switches, alternate feeders, and loads. A radial topology is assumed since it is commonly used in the utilities. Loads are modeled as constant active power loads (constant P). The model uses load flow calculations to check feeders current and voltage limits. Failures in the power distribution network due to disaster can be modeled by faulty feeders or out-of-service transformers. The power system model is then used to calculate the available power to the critical infrastructure e.g. a hospital.

C. Water System Model

The water distribution model defines the modeling properties of the network that distributes water to different critical infrastructures (including a hospital) with appropriate quantity and pressure. The model consists of different components including water storage facilities such as reservoirs and water tanks, a piping network for distribution of water to the consumers, valves to limit the pressure or flow at a specific point in the network, pumps to increase the water flow and output nodes where the water is consumed. Loads are modeled as constant water demand nodes. A failed pump or a broken pipe can be modeled to simulate failures in the water system due to a disaster. Newton-based global gradient algorithm (also known as the Todini and Pilati method [12]) is used to determine the water steady state in terms of water flows values at each pipe and hydraulic heads at each junction according to the water demand curve at each junction and considering the relative physical limits (e.g. pipes length, diameter).

IV. Ordinal Optimization Application

Ordinal Optimization (OO) is a new optimization theory introduced by Ho in the 90s for providing fast Good Enough solutions for complex simulation based optimization problems [13]. It has been applied to solve many problems in different disciplines such as power systems, communication networks, topology design in computer networks, resources allocation in manufacturing systems, scheduling of parallel computing systems, and robotics motion control systems. Ordinal optimization tries to overcome difficulties in existing optimization theories in solving problems that has exponential growth in its search space and computational complexity in its simulation models. Ordinal Optimization is based on two main concepts: **1) Order Comparison**: it is easier to determine order than value, i.e. determining $A > B$ is easier than determining the value of A-B=? and **2) Goal Softening**: instead of looking for the best for sure, we look for good enough with high probability. Using these two concepts, ordinal optimization methods provide a set of Good Enough solutions in an order of their performance.

In many practical applications, it is enough to find good enough solutions instead of insisting on finding the true optimum solution which may exhaust the available computational resources. This rational motivates the application of ordinal optimization to the resources allocation problem addressed in this paper. After a disaster, disaster responders are under pressure to save lives and mitigate disaster impacts. In these emergency situations, they may accept a fast good enough solution instead of waiting for the optimum one. Also, this application can be very useful for playing response scenarios in planning and training activities. The application procedure of Ordinal Optimization can be summarized as follows:

1) Randomly or heuristically sample *N* solutions from the entire solutions space
2) Use a crude and computationally fast model to estimate the performance of these *N* solutions
3) Estimate the Ordered Performance Curve (OPC) class of the problem and the error level of the crude model. Then, specify the size of the good enough set g and the required alignment level *K*
4) Use the Universal Alignment Probability Tables to calculate the size of the selected set *s=f(g,k/OPC class, error level)*
5) Select the observed top s solutions of the *N* as estimated by the crude model as the selected set *S* The theory of OO ensures that *S* contains at least s truly good enough solutions with probability no less than 0.95

As can be seen from the above procedure, the key idea of ordinal optimization is to find a selected set {S} of solutions with an acceptable probability to be a member of the good enough set G as shown in Fig. 2. The good enough set is defined as the top n solution of the entire solutions space Θ . Therefore, the problem is changed from finding the optimum resources distribution over the entire space to finding a set of distributions that has an overlap with the top n solutions in the entire solutions space Θ.

A. OPC Analysis

The size of the selected set S is determined by the shape of the Ordered Performance Curve (OPC). The OPC cure is a conceptual plot of the candidate solutions as a function of their ordered performance i.e., the best, the second best, and so no. There are five classes of OPC curves [13]. The five

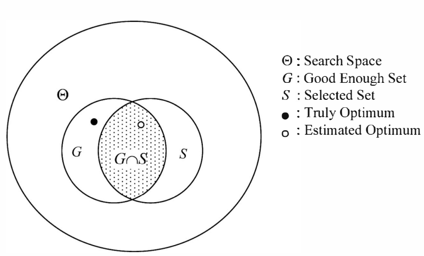

Fig. 2. Ordinal Optimization [13].

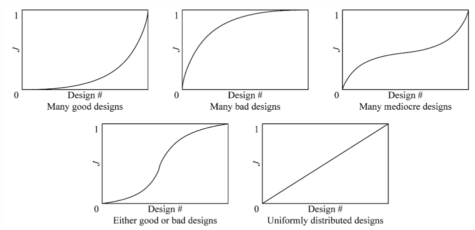

Fig. 3. OPC Classes [13].

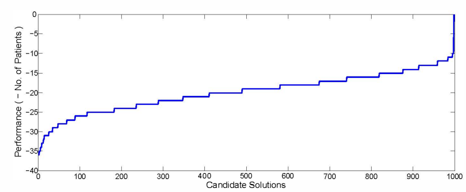

Fig. 4. OPC Plot for the Test System.

classes as shown in Fig. 3 are: Flat, Steep, Bell, U-shaped, and Neutral, respectively. The OPC class can be obtained by past experience or by a one-time pre-processing over entire solutions for a particular problem. This exercise is useful to understand the shape of the solution space of the problem of interest. The OPC plot for the test system used in this paper is shown in Fig. 4 . It can be seen that the OPC class for this problem is a Bell class. It means that most of the solutions are in the moderate region.

B. Optimization Algorithm

The resources allocation problem in disaster response is a combinatorial constraints optimization problem. The objective of the optimization problem is to maximize the number of saved lives. This function is represented by the output of the hospital model in i2Sim which measures the number of treated patients in the hospital. In this paper, we propose an Ordinal Optimization based approach to solve this problem in two stages. In the first stage, we check for the solution feasibility. A solution is represented by a set of distribution ratios in i2Sim model. A feasible solution is a solution that does not violate resources supply constraints in the i2Sim model. We use the i2Sim model as a crude model to filter out unfeasible solutions and rank the feasible ones. Then, the OPC class and selection parameters, g and k, are determined. In the second stage, we employ the domain simulators to check the physical constraints on the selected solutions. Typical physical constraints include voltage and current constraints in the power system and pressure constraints in the water system. The flow chart for the proposed algorithm is shown in Fig. 5.

V. Test Case

The proposed approach was applied to a hypothetical disaster event. The i2Sim model, shown in Fig. 6 consists of three production cells representing: a hospital, a power substation, and a water pumping station. The HRT data represents actual facilities [14]. A power distribution model was developed to map the power substation topology. The power model represents a typical radial configuration of distribution

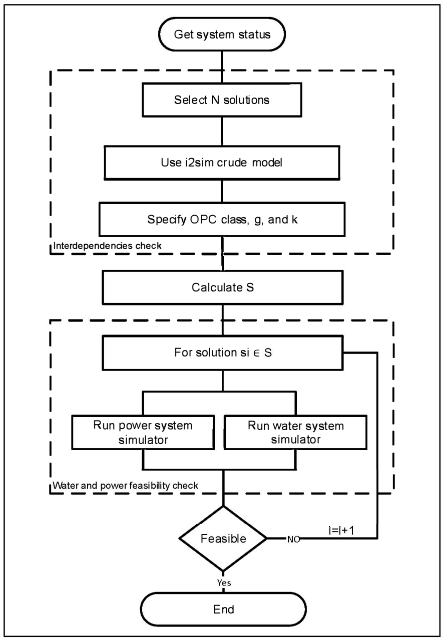

Fig. 5. Optimization Algorithm.

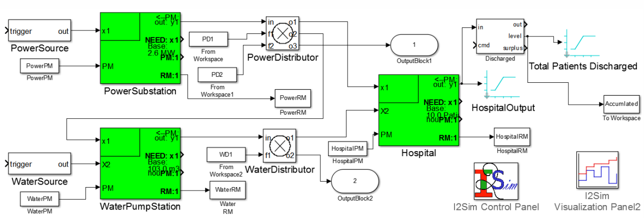

Fig. 6. i2Sim Model.

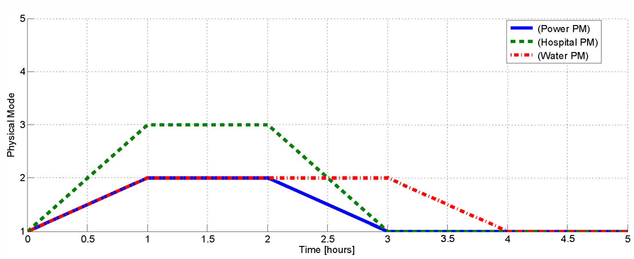

Fig. 7. Physical Modes in i2Sim Model.

system with two supplying transformers and four feeders. An EPANET model was used to model the water distribution network feeding the hospital. It represents an open radial topology with two independent water sources equipped with two pumps and one tank. The optimization algorithm was implemented in MATLAB and integrated with the simulation models using DR-NEP database. The disaster events were modeled by varying Physical Modes (PM) values in the iSim model as shown in Fig.7. In i2Sim ontology, PM=1 means no damage to the infrastructure and PM=5 means completely damaged.

Simulation scenario was assumed to have 5 hours duration

TABLE I. SIMULATION RESULTS (%)

Time Step	PD1	PD2	PD3	WD1	WD2
0	70	30	0	80	20
1	10	90	0	0	100
2	70	30	0	40	60
3	70	20	10	80	20
4	60	10	30	60	40
5	70	10	20	50	50

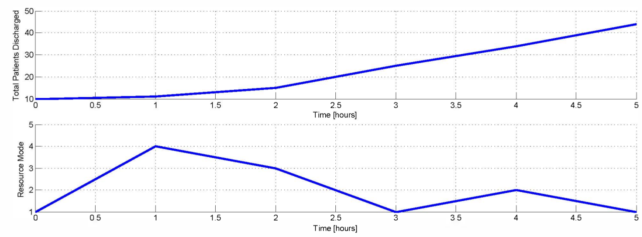

Fig. 8. i2Sim Simulation Results.

with one hour time step. Results have shown that 44 patients can be treated in the hospital utilizing the available power and water resources in this scenario. The best distribution ratios for the power and water distributors at every time step are shown in Table I. PD1, PD2, and PD3 are the outputs of the power distributors while WD1 and WD2 are the outputs of the water distributors. The hospitals output and values of its Resource Mode (RM) during the simulation are shown in Fig. 8. RM value in i2Sim measures level of resources availability: RM=1 means all resources are available while RM=5 means no resources are available. It can be seen from the figure that hospitals output was affected by physical damages in the power substation and water station.

VI. CONCLUSION

During disasters, effective response plays vital role in saving lives. An optimum allocation of available resources can greatly improves response effectiveness. The interdependencies between different infrastructures play crucial role in the optimization process. In this paper, a simulation-based tool for helping disaster responders is proposed. The DR-NEP simulation platform was used to take infrastructures interdependencies into consideration. An Ordinal Optimization based approach was developed to find the optimal allocation of resources, power and water, for a disaster event. The output of a hospital in terms of number of discharged patients was taken as a performance measure. There are other resources that could affect the disaster response such as transportation availability, medical supplies, and natural gas. Inclusion of these resources in the problem is part of the future work plan. In addition, disaster scenarios with multiple events and cascading effects will be considered.

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